A close view on the protoplanetary disk in the Bok globule CB 26

R. Launhardt[1], B. Stecklum[2], and A.I. Sargent[1]

[1] Astronomy Department, California Institute of Technology, Pasadena, CA 91125
[2] Thüringer Landessternwarte Tautenburg, 07778 Tautenburg, Germany

Abstract. We present new sub-arcsecond-resolution near-infrared polarimetric imaging and millimetre interferometry data on the circumstellar disk system in the Bok globule CB26. The data imply the presence of a $M \geq 0.01 \, M_\odot$ edge-on-seen disk of $> 400 \, \mathrm{AU}$ in diameter, being in Keplerian rotation around a young $\sim 0.35 \, M_\odot$ star. The mm dust emission from the inner 200 AU is highly optically thick, but the outer parts are optically thin and made of small dust grains. Planetesimal growth in the inner disk could neither be comfirmed nor excluded. We argue that the CB 26 disk is a very young protoplanetary disk and show that it is comparable to the early solar system.

1   Introduction

Observations of protostellar systems and their prominent jets and outflows suggest that accretion disks start to form very early during the main accretion phase. These disks live much longer than the central protostar needs to build up most of its mass. When the initial protostellar core is dispersed by accretion and outflows, the central star still accretes matter at low rates from the surrounding disk. Typical disk life times around low-mass stars were shown to be at least $10^7 \, \mathrm{yrs}$ and their masses (typically 0.01-0.1 $M_\odot$) do not seem to decrease considerably during this time [2]. Theoretical and laboratory studies show that the timescale for grain growth and planetesimal formation is shorter than the typical disk life time. Such disks should soon evolve into protoplanetary disks. Although the direct detection of planetary-mass bodies in such disks will be extremely difficult, indirect effects of larger bodies, such as a change in the dust opacity spectrum, should be observable with current or near-future techniques.

CB 26 (L 1439) is a small ($d \sim 0.15 \, \mathrm{pc}$), slightly cometary-shaped Bok globule at a distance of $\sim 140 \, \mathrm{pc}$ [7]. Located at the south-east rim of the globule is a small bipolar near-infrared (NIR) nebula. The central star is not visible, even at $2.2 \, \mu\mathrm{m}$. The spectral energy distribution together with the bolometric luminosity of $\geq 0.7 \, L_\odot$ suggest the presence of a low-mass Class I YSO in CB 26. We observed strong submm/mm dust continuum emission from this source showing a thin extended envelope with an unresolved condensation at $10''$ resolution [5], [7], [3]. No molecular outflow has been detected yet.

2   Implication of a circumstellar disk from NIR data

On JHK near-infrared images obtained with the MAGIC camera at the Calar Alto 3.5-m telescope, we found a small bipolar reflection nebula in the Bok
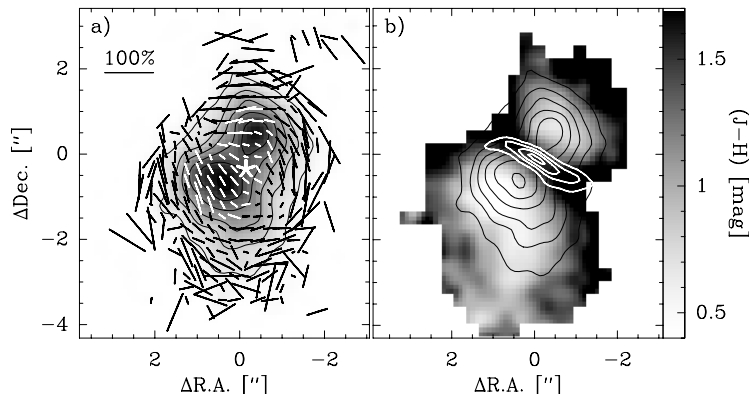
Fig. 1. a) K-band image of the CB 26 NIR nebula with polarization vectors superimposed. The white star marks the center of the polarization pattern, i.e., the location of the illuminating source.   **b)** Grey-scale image: J–H color map of the NIR reflection nebula. Darker regions represent higher extinction. The outer boundary is due to an intensity cut-off level. Overlayed are the contours of the K-band emission from the reflection nebula (black) and of the 1.3 mm dust continuum emission from the circumstellar disk. The K-band image and color map are from [8].

globule CB 26 within the error ellipse of the IRAS source 04559+5200 [8]. Subsequent NIR imaging polarimetry confirmed the bipolar structure of this source. The two lobes are separated by an extinction lane which is most obvious in the J–H color map (Fig. 1b). Very high polarization degrees were detected in the lobes, presumably caused by single scattering at small dust grains. The orientation of the polarization vectors corresponds to a system consisting of a young star surrounded by both a circumstellar disk and a thin envelope. The polarization pattern indicates that the disk is seen almost edge-on causing the band of enhanced extinction in between the scattering lobes. At the very center, the polarization vectors are aligned linearly. This could be either due to photons scattered back from the envelope onto the disk or because of multiple scattering in the outer disk regions. The location of the illuminating source was derived to an accuracy of $0.''3$ by minimizing the mean square scalar product between polarization vectors in the lobes which are probably due to single scattering and their corresponding normalized radius vectors. The central source is located behind the extinction lane, i.e., at the center of the disk (Fig. 1a).

3   Direct observations of dust and gas

CB 26 was observed with the Owens Valley Radio Observatory (OVRO) millimeter-wave array during 2000. We obtained wide-band continuum maps at 1.3 and 2.7 mm and a ^{13}CO(1–0) map with a spectral resolution of 0.17 km/s. The angular resolution of the maps is $\sim 1.''2 \times 0.''8$ at 2.7 mm and $\sim 0.''5 \times 0.''3$ at 1.3 mm, respectively. The observations are described in more detail in [7].
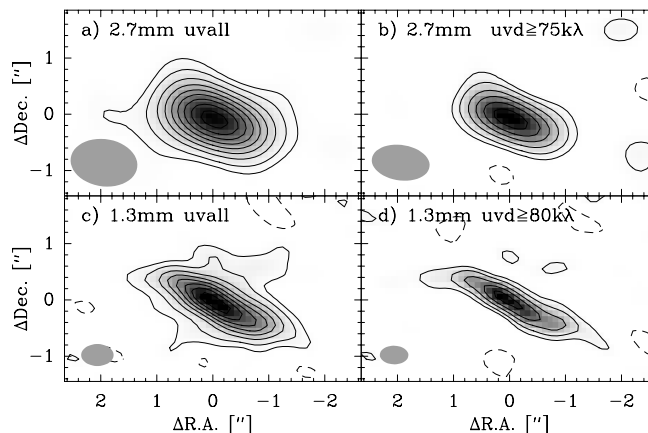
Fig. 2. Dust continuum emission from the CB 26 disk: OVRO results (from [7]). a) and c) show the 3 and 1mm maps synthesized from all uv data. b) and d) show maps derived from long uv spacings only. The synthesized beams (FWHM) are shown as grey ellipses at the lower left corners. Contour levels are in steps of (-2,2,4 to 22 by 3) times 1σ rms. a) $\sigma = 0.6$ mJy/ $1\rlap{.}''2 \times 0\rlap{.}''84$ beam. b) $\sigma = 0.75$ mJy/ $1\rlap{.}''0 \times 0\rlap{.}''63$ beam. c) $\sigma = 1.3$ mJy/ $0\rlap{.}''58 \times 0\rlap{.}''39$ beam. d) $\sigma = 1.4$ mJy/ $0\rlap{.}''50 \times 0\rlap{.}''32$ beam.

The dust continuum maps show an elongated source with a position angle of $60 \pm 3°$ (from N to E; Fig. 2). The position and morphology of this source suggest that the emission originates from the circumstellar disk implied from the NIR data [8]. Figure 1b shows that the dust continuum emission matches well the extinction lane at the center of the NIR reflection nebula. At 3 mm we derive a projected FWHM source size of (160 ± 10) AU $\times < 60$ AU with no signature of an extended envelope. The 1 mm images show a narrow lane and a small envelope extending perpendicular to the disk. The disk height remains unresolved at even the highest angular resolution of $0\rlap{.}''3$, confirming that it must be seen almost edge-on. The projected FWHM size of the 1.3 mm disk is (220 ± 20) AU $\times \leq 20$ AU ($\frac{1}{2}$ of the HPBW in that direction). The actual scale height of the inner disk where the mm emission arises is probably much smaller. The disk has a symmetric $20°$ warp outside $R \sim 100$ AU and is traced out to ~ 200 AU. The total flux densities derived from the OVRO maps are $S_{2.7\mathrm{mm}} = (22 \pm 5)$ mJy and $S_{1.3\mathrm{mm}} = (150 \pm 30)$ mJy. At 1.3 mm, the IRAM 30-m single-dish flux of the unresolved component is completely recovered (160 mJy; [5]). A simple decomposition yields 1.3 mm flux densities for the disk and envelope of $S_\nu(\mathrm{disk}) = (80 \pm 20)$ mJy and $S_\nu(\mathrm{env}) = (70 \pm 20)$ mJy, respectively. Assuming $T_\mathrm{d} = 30$ K, $\kappa_\mathrm{d}(1.3\mathrm{mm}) = 1$ cm^2 g^{-1} of dust and $M_\mathrm{H}/M_\mathrm{d} = 110$ we derive an envelope mass of $M_\mathrm{H}(\mathrm{env}) = (0.03 \pm 0.01)$ M$_\odot$. The total mass of the more extended envelope seen in the single-dish maps is (0.12 ± 0.05) M$_\odot$ ([3], [7]). The disk appears to be considerably smaller in the 3 mm dust emission than at 1 mm. For the central $R \leq 100$ AU we derive a 1–3 mm spectral index $\alpha = 2 \pm 0.5$ (envelope subtracted). Further out α increases to reach 3.5-4 at $R \sim 180$ AU.

At larger radii the 3 mm emission is not longer traced. This implies that most of the dust mass in the outer warped part of the disk is contained in classical, μm–mm size grains with a spectral index of the dust opacity of $\beta \sim 1.5 - 2$. The mm dust emission from the inner $\sim$200 AU of the disk is highly optically thick. Therefore, no constraints can be made on β without better constraints on the temperature distribution and extensive modeling. Assuming that the 3 mm emission is mostly optically thin, a lower limit to the disk mass can be derived. Adopting $\kappa_\nu(1.3\text{mm}) = 0.02\,\text{cm}^2\,\text{g}^{-1}$ of ISM, $\beta = 1$, $T_o = 1000\,\text{K}$ at $r_o = 0.1\,\text{AU}$, $T \propto r^{-0.4}$, and surface density $\Sigma \propto r^{-1.5}$ as 'typical' disk parameters, we derive $M_H(\text{disk}) \geq 0.01\,M_\odot$, a value which is typical for disks around T Tauri stars [2].
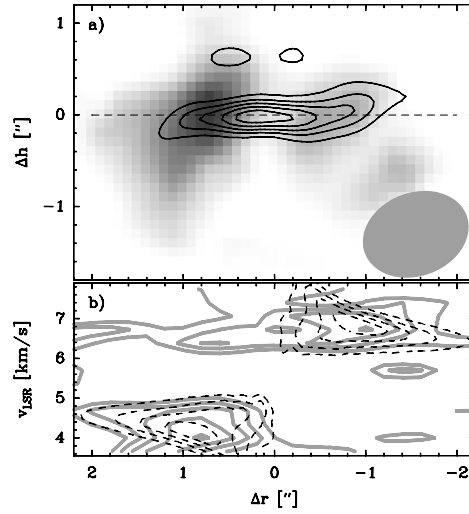

Fig. 3. ^{13}CO(1–0) emission from the CB 26 disk: OVRO results. a) grey-scale: integrated intensity of the ^{13}CO(1–0) emission. The synthesized beam (FWHM) is shown as grey ellipse in the lower right corner. Overlayed are the contours of the 1.3 mm dust continuum emission from the disk. The image is rotated by 30°.   b) Position-velocity diagram of ^{13}CO along the plane of the disk (dashed line in a). Thick grey contours show the observed velocity field (27, 45, 63, 81, 99% of max). Dashed contours show the modeled emission from a Keplerian disk around a 0.35 $M_\odot$ star.

Strong ^{13}CO(1–0) emission ($T_R^* \sim 20\,\text{K}$) was detected from the outer parts of the CB 26 disk, but there seems to be a lack of emission from the central part (Fig. 3a). The line is double-peaked with the blue part coming from the N-E side and the red part from the S-W side of the disk. Emission at the systemic velocity of the envelope $v_{\text{LSR}} = 5.5\,\text{km}\,\text{s}^{-1}$ ($\Delta v \sim 0.6\,\text{km}\,\text{s}^{-1}$) is self-absorbed and/or resolved out. Although the current spectral data cover only a small velocity range ($3 \leq v_{\text{LSR}} \leq 8\,\text{km/s}$), they could be well-modeled by a Keplerian disk rotating around a $(0.35\pm0.1)\,M_\odot$ star (Fig. 3b). The high-velocity line wings from the inner parts of the disk expected for a Keplerian disk are not recovered in the

data because of the small band width. There is some 'forbidden' red-shifted emission from the 'blue side' of the disk which may be due to infall or outflow. A more detailed study of the kinematics of this disk-envelope system is subject to follow-up observations.
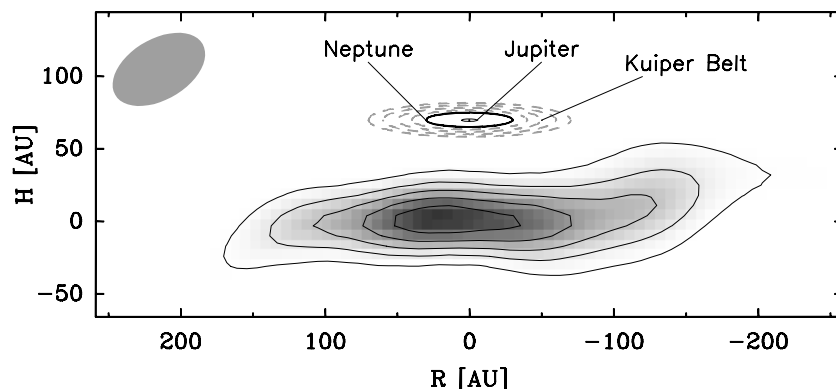
4 Conclusions

Fig. 4. The CB 26 disk compared to the solar system. The grey scale image and contours show the 1.3 mm dust continuum emission from the CB 26 disk as observed with OVRO. For comparison, the solar system is represented by the orbits of Jupiter and Neptune and the Kuiper Belt (40–70 AU).

From OVRO millimeter interferometric observations we discovered and resolved the thermal dust continuum and ^{13}CO line emission from the circumstellar disk in CB 26 which was recently implied by high-resolution NIR polarimetric observations. The disk is seen edge-on as predicted by the NIR observations and matches well the extinction lane at the center of the bipolar NIR reflection nebula. It has a FWHM diameter of (220 ± 20) AU and a maximum (traced) diameter of $\sim$400 AU. The (projected) scale height remains unresolved ($h \leq 20$ AU). For the first time, we directly detect a warp in a young circumstellar disk. The warp affects the disk outside $R > 100$ AU. Like in many extra-galactic disks, such a warp could be caused by a small external disturbance like, e.g., an encounter with a nearby star. However, the actual cause of the warp is not known.

The 1.3 mm dust emission from the inner $R \sim 100$ AU of the disk is highly optically thick, and only a lower limit to the total disk mass $M_{\rm H}({\rm disk}) \geq 0.01\,{\rm M}_\odot$ can be derived from the 3 mm emission. Due to the high optical depths, no constraints on the dust opacity spectral index β and possible planetesimal growth in the inner undisturbed part of the disk can be drawn. The dust emission from the outer parts of the disk is optically thin and arises from small 'classical' grains. However, since the outer disk is obviously disturbed as indicated by the

warp and has much lower particle densities, this does not exclude that particle growth in the inner disk has already taken place. The small disk envelope, which extends above and below the plane of the disk and may be related to an yet undetected outflow or a disk wind, contains $\sim (0.03 \pm 0.01)\,\mathrm{M_\odot}$. Further $(0.12 \pm 0.05)\,\mathrm{M_\odot}$ are contained in a more extended envelope ($\sim 3000\,\mathrm{AU}$ in diameter) which extends mainly to the north-east and may represent the remnant, nearly dispersed protostellar core from which this system has formed [3].

Strong ^{13}CO emission shows that the disk must be still gas rich, that it is rotating, and has a kinetic temperature of order $30\,\mathrm{K}$ outside $R \sim 100\,\mathrm{AU}$. The rotation curve is consistent with Keplerian rotation around a $(0.35 \pm 0.1)\,\mathrm{M_\odot}$ star. With a total luminosity of $\geq 0.7\,\mathrm{L_\odot}$, its large disk and its close connection with the parental cloud core, the CB 26 system resembles an intermediate M type T Tauri star of age $< 10^5$ yrs. The lack of a dense, centrally peaked cloud core with spectroscopic infall signatures as well as of a prominent molecular outflow indicates that the system has already passed its main accretion phase. Therefore, we conclude that this is a young protoplanetary disk.

If compared to the solar system today, the CB 26 disk is ~ 2.5 times larger than the outer Kuiper Belt (Fig. 4). However, the optically thick and undisturbed part inside the warp has approximately the size of the Kuiper Belt. The total mass in the CB 26 disk (if all the gas is still there) is at least 10 times higher than the planetary mass in the solar system. However, the dust mass in the CB 26 disk could be comparable or lower than the rocky mass in the solar system. These numbers depend critically on the dust properties which are not well-known. Altogether, the CB 26 system appears like a 2–3 times lower-mass equivalent to the early solar nebula at the verge of forming planetesimals and probably planets.

References

1. S.V.W. Beckwith, Th. Henning, Y. Nakagawa: 'Dust properties and assembly of large particles in protoplanetary disks'. In: *Protostars and Planets IV*, ed. by V. Mannings, A.P. Boss, S.S. Russell (Univ. of Arizona Press 2000) pp. 533–558
2. S.V.W. Beckwith, A.I. Sargent, R. Chini, R. Güsten: AJ **99**, 924 (1990)
3. Th. Henning, S. Wolf, R. Launhardt, R. Waters: 'Measurements of the magnetic field geometry and strengths in Bok globules', ApJ (submitted)
4. R. Launhardt: Star formation in Bok globules, PhD thesis, University of Jena (1996)
5. R. Launhardt, Th. Henning: A&A **326**, 329 (1997)
6. R. Launhardt, N.J. Evans II, Y. Wang, D.P. Clemens, Th. Henning, J.L. Yun: ApJ **119**, 59 (1998)
7. R. Launhardt, A.I. Sargent, H. Zinnecker: 'A protoplanetary disk in the Bok globule CB26?', ApJ (submitted)
8. B. Stecklum, O. Fischer, R. Launhardt, Ch. Leinert: 'Discovery of a circumstellar disk in the Bok globule CB26', ApJ (submitted)